

Destruction of wide binary stars in low mass elliptical galaxies: implications for initial mass function estimates

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ABSTRACT

We discuss the effects of destruction of wide binaries in the nuclei of the lower mass giant elliptical galaxies. We show that the numbers of barium stars and extrinsic S stars should be dramatically reduced in these galaxies compared to what is seen in the largest elliptical galaxies. Given that the extrinsic S stars show strong Wing-Ford band and Na I D absorption, we argue that the recent claims of different initial mass functions from the most massive elliptical galaxies versus lower mass ellipticals may be the result of extrinsic S stars, rather than bottom-heavy initial mass function.

Key words: stars:binaries – stars:chemically peculiar – galaxies:stellar content – supernovae:general

1 INTRODUCTION

Despite the fact that most stars are members of binary systems, binary stellar evolution is usually neglected in modelling of the spectral energy distributions of galaxies (although see e.g. Han et al. 1995). This decision is made as a basic simplification, in part because it has not, to date, been clear how binary evolution would affect most of what is seen in optical light, and in part because binary population synthesis is extremely complicated, with large numbers of parameters which are not particularly well-constrained by observations (see e.g. Belczynski et al. 2008 for a discussion of a particular binary population synthesis code). Furthermore, while we will show evidence to the contrary in this paper, one might initially expect that the effects of binary evolution would not vary much from galaxy to galaxy.

Heggie’s Law (1975) states that hard binaries get harder while soft binaries get softer – i.e. binaries whose binding energy is larger than the mean kinetic energy of single stars in their local neighborhood will tend to become closer with time, while binaries with binding energies less than the local mean stellar kinetic energy will tend to become wider with time until they are eventually dissolved into two single stars. The consequences of Heggie’s Law are generally well-appreciated, if not fully understood, in the context of globular clusters. For example, the hardening of binaries in globular clusters supplies kinetic energy to the single stars in the clusters, holding up the collapses of star clusters in a manner somewhat analogous to the manner in which nuclear fusion holds up the collapses of stars (see e.g. Sugimoto & Bettweiser 1983; Fregeau 2008).

In the context of field populations of galaxies, it has been shown that the absence of wide binaries in the Galactic halo can be taken as evidence against massive compact halo objects (i.e. MACHOs) supplying the bulk of the dark matter in the Milky Way (Yoo et al. 2004). There has been relatively little appreciation, however, of how removing long period binaries from a stellar population affects integrated stellar light. Traditionally, in fact, stellar population synthesis models for understanding galaxy evolution have ignored binaries almost entirely, except with respect to binary models for producing the ultraviolet upturn in elliptical galaxies (e.g. Han et al. 2002; Han et al. 2007), and, of course population synthesis calculations aimed at unequivocally binary populations like X-ray binaries and double neutron stars (e.g. Belczynski et al. 2008). In this Letter, I will show that the cutoff period varies considerably through different classes of stellar systems, and that this difference affects whether Roche lobe overflowing red giants will be present in different classes of galaxies. I will show further that these binary systems may then have profound implications for the observational appearance of different classes of galaxies.

2 BINARY DISSOLUTION TIMESCALES

Binney & Tremaine (2009) give the dissolution timescale of a binary as:

$$t_d = 15 \text{Gyr} \left(\frac{K_{diff}}{0.002} \right) \left(\frac{\sigma_{rel}}{40 \text{km/sec}} \right) \left(\frac{M_b}{2M_\odot} \right) \left(\frac{M_p}{M_\odot} \right)^{-1} \left(\frac{0.05 \text{pc}^{-3}}{n} \right) \left(\frac{10^4 \text{AU}}{a} \right), \quad (1)$$

where $K_{diff} = \frac{0.022}{\ln \Lambda}$ (and $\Lambda = \frac{\sigma_{rel}^2 a}{GM_p}$), so that $K_{diff} \approx 0.002$ for nearly all galaxies; σ_{rel} is the velocity dispersion of the scattering stars, M_p is the mass of the star perturbing the binary, M_b is the mass of the binary, n is the number density of stars in the local region, and a is the orbital separation of the binary.

Now, let us consider two relatively extreme giant elliptical galaxies: M87, the central galaxy in the Virgo Cluster, and NGC 4458, a small galaxy in the Virgo Cluster. For M87, the central velocity dispersion is about 400 km/sec, and the central density is about 200 stars per cubic parsec (Gebhardt & Thomas 2009). For NGC 4458, the central density is about 2800 L_\odot/pc^3 (Gebhardt et al. 1996), and the central velocity dispersion is 85 km/sec (van Dokkum & Conroy 2011). In general, the fundamental plane relation (Dressler et al. 1987) shows giant elliptical galaxies which fit on the plane will become significantly denser and have significantly lower velocity dispersions as their masses drop. For a 10 Gyr old population in a dynamical environment like that of M87, binary separations of up to about 20 AU will be possible in the core; for a galaxy like NGC 4458, binary separations of about 0.4 AU will be possible.

3 BINARY EVOLUTION AT AROUND 1 AU SEPARATION

Two important classes of objects have orbital periods of order 1 year. They may be destroyed in the cores of the smallest giant elliptical galaxies, but not in the cores of the largest galaxies. They are symbiotic stars, and barium stars/extrinsic S stars.

First, let us consider the case of symbiotic stars. These are binary systems which contain compact objects which accrete from a highly evolved companion star – either a red giant or an asymptotic giant branch star. While there are a few neutron star symbiotic binaries, the vast majority of the symbiotic stars have white dwarf accretors (Belczynski et al. 2000). The orbital periods of the catalogued symbiotic stars range from a little over 200 days to 5700 days (Belczynski et al. 2000). Even the shortest period symbiotics have separations of about 0.9 AU (assuming $P = 250$ days and a total system mass of about $1.5M_\odot$). One reason for particular interest in the symbiotic stars is that a disproportionate fraction of recurrent novae occur in symbiotic stars, as are a disproportionate fraction of the steady supersoft sources (e.g. Sokoloski 2003). It is not generally considered that these objects represent a large fraction of Type Ia supernovae (e.g. Schaefer 2014), but searching for a deficit of central Type Ia's in dense galaxies would represent an additional possible test.

The other class is a group of stars with enhancements in their s-process element abundances – barium stars, CH stars and extrinsic S stars (sometimes called Tc-poor S stars). Barium stars (see Bidelman & Keenan 1951 for the discovery of the class, and e.g. Warner 1965; McClure 1985 for a working definition of the class) are G/K giants which show exceptionally strong absorption lines from s-process elements – especially barium and strontium. CH stars (Keenan 1942) represent the Population II analogs of the barium stars. S stars in general represent the class of cool stars rich in s-process elements (Merrill 1922 – although at the time of the establishment of the category, they were called S stars with the letter S being chosen, apparently, arbitrarily with the connection to the s– process coincidental). It has become appreciated in recent years that *all* barium stars are found in wide binaries (i.e. with orbital periods of at least 600 days – Jorissen & Mayor 1992) with white dwarf companions, in accord with theoretical predictions (e.g. Iben & Renzini 1983). This finding has led to a model for their production in which a star donates most of its envelope to its companion star after it evolves off the main sequence, so that the companion star's new abundances become the abundances of the interior of the originally more massive star (see e.g. McClure & Woodsworth 1990; Han et al. 2002). Extrinsic S stars are the S stars thought to form through binary stellar evolution, as descendants of the barium stars. There also exist intrinsic S stars, which are thought to form as s-process elements are raised to the surface in the third dredge-up in the evolution of a moderately massive single stars. The most common means of distinguishing between the two is by searching for lines from Tc, an s-process element with a half-life of order a million years – similar to the lifetimes of the intrinsic S stars, but much shorter than the lifetimes of the extrinsic S stars.

3.1 Implications for supernova progenitors

The implications for our understanding of Type Ia supernova progenitors are quite clear. If symbiotic stars dominate the progenitors of Type Ia supernovae in old stellar populations, then there should be a strong deficit of such objects seen from the centers of small elliptical galaxies. The Type Ia supernova rates on the outskirts of these galaxies, where the stellar density has dropped, should not be affected. Searching the centers of the highest surface brightness galaxies is not easy, but may pay large dividends. On a related note, any elements predominantly produced in recurrent novae may be preferentially more abundant in the largest giant ellipticals than in smaller giant ellipticals.

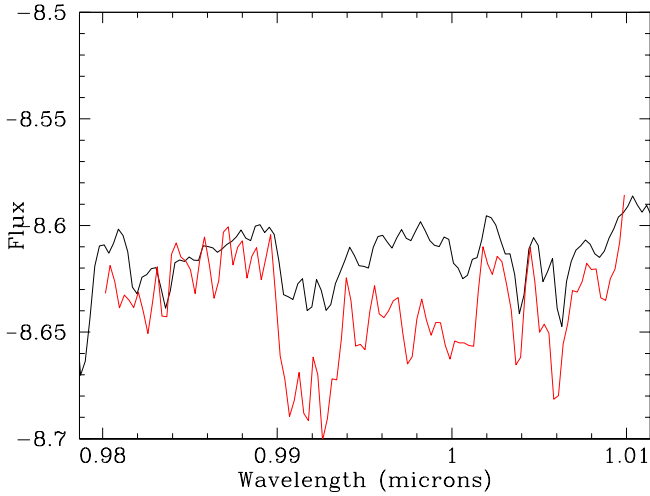


Figure 1. The spectra of two similar temperature stars from the IRTF library (Rayner et al. 2009). The upper curve, in black, is the spectrum of HD18191, an M6III star. The lower curve, in red, is the spectrum of SU Mon, a S6 star. The continua shortward of the Wing-Ford band are similar, while the spectrum along the Wing-Ford band shows suppressed flux for the S star, indicating that its Wing-Ford band strength is much larger. Some S stars show even deeper Wing-Ford bands, but these are not in the IRTF libraries.

3.2 S stars: implications for understanding integrated light spectroscopy from galaxies

The use of certain near-infrared spectral features to constrain the initial mass function of stars has been suggested for quite some time. Whitford (1977) suggested that the suggested that the FeH band at 9916 Å (discovered by Wing & Ford in 1969, and hence often called the Wing-Ford band) could be used to estimate the amount of light from dwarf stars in old stellar populations, but did not detect the band in a sample of seven galaxies he observed. Hardy & Couture (1988) did detect the band, but noted that the presence of a nearby TiO feature would often complicate the interpretation of such measurements. Using more sophisticated models for the integrated light from galaxies, van Dokkum & Conroy (2010) showed that the Wing-Ford band in the centers of giant elliptical galaxies is much stronger than expected from standard simple stellar populations models. Later, in Conroy & van Dokkum (2011), they argued further that the much smaller elliptical galaxy NGC 4458 had an initial mass function much closer to the Salpeter IMF, again on the basis of its Wing-Ford band. An alternative method for testing the initial mass function has also been proposed recently, and has also found a higher M/L ratio in the most massive galaxies than is expected from a Salpeter, Kroupa, or Chabrier IMF (Cappellari et al. 2012), but this work examines *only* the stellar mass to light ratio, and can give the same results for a bottom-heavy IMF dominated by dwarf stars, or a top heavy IMF with larger numbers of black holes, neutron stars and white dwarfs.

It has also been found, however, that stars rich in s-process elements show strong Wing-Ford bands (Wing 1972; Lambert & Clegg 1980), leading to a flux reduction of about 0.1-0.2 magnitudes. This can also be seen from the IRTF spectra of S stars (Rayner et al. 2009 – see also figure 1). Since the Wing-Ford feature in the giant elliptical galaxies is only about 0.02 magnitudes deeper than expected from a Salpeter initial mass function, only about 10% of the giants’ light needs to come from S stars for the S stars to explain the deviation from the predictions of a Salpeter IMF. Since the Wing-Ford band itself is quite broad with the deep part of the absorption spanning about 40 Å, and the whole band spanning more than 100 Å, the smearing due to the few hundred km/sec velocity dispersions in elliptical galaxies will be negligible – unlike the case for narrow spectral features which might be strongly affected.

It should be noted that the empirical spectral libraries used by van Dokkum and Conroy (2010) explicitly excluded giants of unusual chemical composition, rather than attempting to estimate the number of such stars and weigh their empirical spectra accordingly. As a result, their models are missing single-star channel S stars for all galaxies, and is also missing the binary channel S stars for galaxies where they can exist. The single star channels are not likely to be especially important for early type galaxies, since the s-process elements reach the surface only during the third dredge up phase of stellar evolution, a process which happens only for relatively high mass stars.

In order to estimate the magnitude of the effect on the Wing-Ford band, we need an estimate of the fraction of giants which are S stars. This is not straightforward to do from the literature, as the number of very cool giants is rather small, and in the CCD era, only recently has there been good enough sensitivity at 9900 Å for spectra at that wavelength to be common. As one manner of estimating the number of S stars, we can rely on the number densities of barium stars, which are identified by features around 4400 Å, and which are thought to be progenitors of the extrinsic S stars, and we can assume that the ratio of S stars to M giants will be similar to the ratio of barium stars to earlier type red giants. We also note that roughly half of the S stars seen in the Milky Way in flux limited surveys are intrinsic and roughly half are extrinsic (e.g. Yang et al. 2006).

Following a suggestion by Han et al. (1995), we restrict the counts of the two classes of objects to those stars brighter than 6th magnitude, so the stars will be members of the Bright Star Catalog (Hoffleit & Warren 1995), and also allows us to be reasonably confident that most of the barium stars will have been identified as such. We also note that the barium stars have been found to show typically the same absolute magnitudes as other G/K giants (e.g. Kemper 1975; Hakkila 1990). Restricting ourselves to giants with spectral classes from G5 to K5, we find 61/1194, or 5.5% of the stars are barium stars – we regard this number as a lower limit, since there does not exist a definitive paper with upper limits that definitively show that all the barium stars are accounted for. This limit is considerably higher than what was estimated through a similar procedure by Warner (1965) – however Warner noted that the barium stars in his sample already skewed toward being around K0 in spectral type, and that relatively fewer normal giants were in that temperature range than is the case for later K-types.

Similarly, about 4% of the M giants in the Bright Star Catalog (Hoffleit & Warren 1995) correspond with S stars in the catalog of Stephenson (1984). Keenan (1954) found that roughly 10% of M giants were S stars as well, and no more recent systematic attempt seems to have been made to estimate the fraction of stars occupying the M-giant region of the color magnitude diagram which are S stars. CH stars account for roughly 30% of halo giants (e.g. Lucatello et al. 2005).

We can thus conclude that removal of the extrinsic S stars from a galaxy will have a significant effect on its apparent initial mass function if the mass function is measured using the Wing-Ford band. If \sim half of the barium stars are as yet unidentified, then the extrinsic S stars may explain the entire effect on the Wing-Ford band, with no need for an altered stellar initial mass function. Another issue, whose effect is not clear, is whether the binary fractions of galaxies vary systematically. Within the Galaxy, there is some suggestive evidence that metal rich stars have a higher binary fraction than metal poor stars (e.g. Riaz et al. 2008), which might also boost the number of S stars in massive galaxies relatively to that in lower mass galaxies. Studies have been done of extragalactic binary fractions only in a few very nearby galaxies. They are within a factor of the few of the disk binary fraction, but with large statistical uncertainties (e.g. Geha et al. 2013).

One clear prediction of a scenario where the S stars are significant contributors to the Wing-Ford band fluxes of galaxies is that the ZrO bands should be stronger in such galaxies as well. In the most comprehensive analysis to date of elliptical galaxies (van Dokkum & Conroy 2012), there is no real sensitivity to these bands. In integrated light, the strong bands near 4600 Å will be swamped out by the light from turnoff stars, while the strong band around 6470 Å is not covered in the spectra, and the region around the strong infrared band of ZrO at about 9300 Å is in the region of strong sky background.

We note that the Na I D absorption line was also presented by van Dokkum & Conroy (2010) as part of the evidence for a bottom heavy initial mass function in giant elliptical galaxies. This line is also strongly enhanced in barium stars and S stars – Warner (1965) estimates that the sodium abundances of the barium stars are roughly 1.2-1.8 times larger than expected for stars of the same iron abundance. Additionally, the [Na/Fe] abundance ratio increases with increasing [Fe/H], at least for super-solar stars in the Milky Way disk (e.g. Edvardsson et al. 1993). The use of solar metallicity template spectra will therefore affect sodium absorption lines much more strongly than most other lines.

An alternative test of the scenario is to look at the central region of the Milky Way. Dynamical encounters there have been suggested to affect the formation rates of X-ray binaries (Maccarone & Patruno 2013; see also a similar suggestion for the inner bulge of M31 from Voss & Gilfanov 2007). In the central regions of the Milky Way, the stellar density can be $\sim 10^6$ stars per pc³ (i.e. in the nuclear star cluster – Genzel et al. 2010). The density remains greater than a few thousand solar masses per cubic parsec out to several parsecs. Since the absolute *K* band magnitudes of the extrinsic S stars are about -5.7 (van Eck et al. 1998), they should have apparent magnitudes of roughly 14 at the distance of the Galactic Center, assuming a distance of 8 kpc, and 5 magnitudes of extinction – these sources should be detectable as S stars in surveys of the Galactic Center, e.g. with FLAMINGOS-2 (Eikenberry 2008).

4 CONCLUSIONS

Binary destruction in the cores of the smaller giant elliptical galaxies is expected. A lack of S stars in these galaxies can provide an alternative explanation for the recent claims of steeper initial mass functions in the biggest giant elliptical galaxies than in smaller ellipticals, eliminating the need to deal with the conflict between those results and other estimates of the dark matter content of the Universe. This idea can be tested by searching for the ZrO bands in giant elliptical galaxies, and by spectroscopic follow-up of giants in the center of the Milky Way relative to giants elsewhere in the Milky Way.

If the Wing Ford band can be confirmed to be dominated, or even affected, by the S stars, the results from Cappellari et al. (2012) showing higher M/L in higher velocity dispersion galaxies remain unaffected by the conclusions of this work. However, the results of Cappellari et al. (2012) have some degeneracies between the functional form of the dark matter density distribution and the stellar mass-to-light ratio. They can also produce higher-than-standard M/L ratios either through top heavy or bottom heavy initial mass functions, with the former producing high M/L ratios due to having more compact objects, and the latter due to having more low luminosity M-dwarfs. Understanding all the systematic effects in stellar population models is thus a key for understanding the root cause of the results of Cappellari et al (2002).

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